*Atmospheric Pollution Research 6 (2015) 382-388*

Atmospheric Pollution Research

www.atmospolres.com

# Micro–scale simulation of atmospheric emissions from power–plant stacks in the Po Valley

**Grazia Ghermandi, Sara Fabbi, Marco Zaccanti, Alessandro Bigi, Sergio Teggi**

*Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Vignolese 905, 41125 Modena, Italy*

## ABSTRACT

The atmospheric dispersion of the $NO_X$ plume that will be emitted from a new power–plant, at present under installation, was simulated at micro–scale with Micro–Swift–Spray (MSS) Model. The plant will be constructed in a residential urban area in the town of Modena (Po Valley, Northern Italy), where low wind speeds and thermal inversions are quite frequent. Simulation results point out a different behavior of urban canopy in influencing the 3D dispersion patterns among urban obstacles, according to atmospheric mixing conditions: in case of moderate wind events, urban canyon phenomena may occur with a consequent increasing of $NO_X$ concentration gradients among buildings, while with low winds the near–field influence of the buildings emphasizes pollutant accumulation. The MSS simulated $NO_X$ concentrations result always much lower than the regulatory limits for air quality. The comparison of simulation results with measured concentration data for $NO_X$ shows the importance of micro–scale dispersion modeling to perform an accurate and reliable assessment of meteorological condition effects on pollutant distribution, and the ability of MSS in providing reliable simulations of atmospheric dispersion.

***Keywords:*** *Micro–scale simulation, urban canopy, plant stacks, low wind, measured concentrations*

***Corresponding Author:***
***Grazia Ghermandi***
☎ : *+39-059-2056120*
🖷 : *+39-059-2056126*
✉ : *grazia.ghermandi@unimore.it*

***Article History:***
*Received: 23 July 2014*
*Revised: 31 October 2014*
*Accepted: 05 November 2014*

**doi:** 10.5094/APR.2015.042

## 1. Introduction

The reduction of pollutant emissions from combustion plants are firm commitments set by the European Commission. The European Commission promotes the "cogeneration" (EU, 2004), i.e. combined production of heat and electricity, because the self–production of electric power reduces the needs of electricity generation from conventional systems. However, the impact of a cogeneration plant on air quality depends on its emission performance but also on the dispersion of its stack emissions in the atmosphere.

In this case study, a new power plant, methane fuelled, consisting of a tri–generation unit and five auxiliary devices (conventional generators), will be installed in the General Hospital of a Northern Italy town (Modena, Central Po Valley, 34 m asl.).

The atmospheric impact at local scale of the stack emissions from this power plant have already been investigated by Ghermandi et al. (2014) which showed how the impact at ground resulted smaller for the emissions by the tri–generation unit than by the conventional boiler, also under meteorological conditions favoring pollutant accumulation in the atmosphere.

Main aim of the present work was to study the dispersion patterns of stack emissions at micro–scale in the urban area close to the General Hospital, where maximum concentration values for the emitted pollutants are expected and where atmospheric dispersion is strongly influenced by building location, distance and height.

The simulations were performed by the Micro–Swift–Spray (MSS) code (Moussafir et al., 2004; Tinarelli et al., 2012) featured in the ARIA INDUSTRY software package. This code includes the mass–consistent diagnostic 3D wind–field model Micro–Swift (Aria Technologies, 2010) and the Lagrangian Particle Dispersion model Micro–Spray (Arianet, 2010) implemented for micro–scale applications, able to simulate the airborne pollutant dispersion among buildings. The model considers non–homogeneous and non–stationary atmospheric turbulent conditions, plume rise effects (Anfossi et al., 1993) and stochastic velocity fluctuations (Thomson, 1987). Plume rise phenomena can be simulated by Micro–Spray in different atmospheric conditions by computing the buoyancy flux of each particle (i.e. plume parcel) according to the exhaust gas exit conditions and the atmospheric stability class. In presence of a ground surface–based thermal inversion layer, the partial penetration of the inversion is simulated through those plume particles that still retain high buoyancy when reaching the top of the inversion layer (Arianet, 2010).

MSS Model performances in approaching complex phenomena were widely tested in the literature and showed a good agreement with Computational Fluid Dynamics (CFD) models (Tinarelli et al., 2007; Tinarelli et al., 2008), with other diagnostic wind flow and Lagrangian particle dispersion models and with experimental data (Hanna et al., 2011).

The simulations were performed under two different atmospheric conditions during winter, the most critical season for air quality in the Po Valley (Ferrero et al., 2011): a low wind (i.e. wind speed <2 m/s) event (prevalent condition at the studied site) and a case of wind speed significantly above the average winter value.

The simulation was focused on $NO_X$ dispersion, being the most critical pollutant for methane fuelled plants: the ground level concentrations of emitted $NO_X$ obtained from the simulations were compared with air quality regulatory limits.

The reliability of MSS Model in simulating dispersion patterns in urban environment according to the daily evolution of atmospheric mixing conditions was evaluated by the correlation between simulated and measured concentration data.

## 2. Case Study

A new power plant will be installed at the General Hospital of Modena in order to supply its total energy demand. It will consist of six devices supplied by methane gas: a tri–generation unit powered by an internal combustion four–stroke engine, three conventional boilers, and two industrial steam generators. Stacks are all 10 m high except for the tri–generator (15 m). The plant design is oversized in order to fulfill the energy demand with safety criteria, and during ordinary operation only three devices will be active: the tri–generator, one boiler and one steam generator. Features and operating conditions of the plant were described by Ghermandi et al. (2014), who estimated the emitted exhaust gas flows from stacks on the basis of the hourly average planned fuel consumption in the monthly mean day. For a daily micro–scale simulation, spanning over a period of 24 hours, a specific hourly modulation of emission patterns for boilers and for steam generators was considered. For the tri–generator, which operates at steady–state conditions, the emission pattern was assumed to be constant throughout the day.

## 3. Model Setup and Data Set

MSS simulation was performed over a 500 m x 500 m horizontal domain, centered at plant position and divided into a regular grid of cells with size of 2 m x 2 m. This domain represents the urban area surrounding the General Hospital where the highest atmospheric impact from the future power plant is expected. The vertical domain is divided into a grid of 20 layers with variable thickness from the ground to 200 m (domain top): the first vertical layer is 2 m thick. The numbered points in Figure 1a show the plant stack locations in the micro–scale domain: boiler (1), steam generator (2), and tri–generator (3). Building geometry (Figure 1b) was drawn out from an urban elevation model provided as a polygon vector file (shapefile) (E.R., 2011) using a GIS software package.

Two days, January 14$^{th}$ and February 6$^{th}$, were selected from the winter 2010 meteorological dataset in order to obtain simulations under widely differing meteorological conditions.

Both simulated and measured meteorological data were used in MSS simulations. Wind speed data were provided by the meteorological station of the Osservatorio Geofisico (University of Modena and Reggio Emilia) located in Modena near the sources. Meteorological simulated data comprise mesoscale vertical wind profiles and mixing height. These data have been provided by the Regional Environmental Agency (ARPA) using the diagnostic model CALMET (Deserti et al., 2001), which requires input meteorological ground measurements and radiosounding profiles of temperature and wind speed (Chandrasekar et al., 2003). Daily patterns for hourly wind speed and for mixing height in the two test days are plotted in Figure 2. In 2010, average winter values of wind speed and mixing height in Modena resulted of 1.7 m/s and 310 m, respectively.

January 14$^{th}$ is characterized by low winds (i.e. wind speed <2 m/s); mixing height pattern clearly shows that stable conditions occur early in the morning and at nightfall, while thermal convection prevails only in the middle of the day. Similar atmospheric conditions, in which stability occurs for most of the day, are unfavorable to pollutant dispersion and are fairly frequent during the winter in the Po Valley (Bigi et al., 2012). On the contrary, on February 6$^{th}$, wind speed values are higher than the average measured value for the whole 2010 winter season and the irregular trend of the mixing height is due to clouds and rainy periods (daily precipitation is 8 mm). This day has been chosen in order to evaluate the dispersion patterns in conditions of moderate wind, which infrequently occur in the studied area.

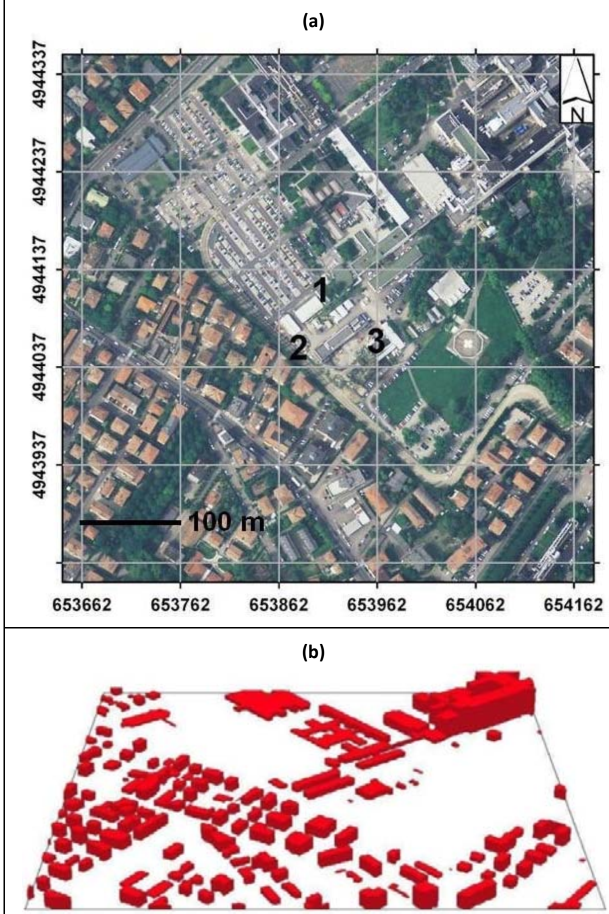


***Figure 1.*** *The studied area in Modena: geographical map* ***(a)*** *and 3D block–shaped structure in MSS* ***(b)****.*

The MSS simulation time step has been set to one hour, consistently with the acquisition time step of meteorological input data.

The same operating conditions consistent with the plant design have been assumed for both simulations; therefore the $NO_X$ emission rate from the plant is the same for the two days. Table 1 reports daily average for exhaust gas temperature and velocity at the exit of the three device stacks during the two test days.

## 4. Results

### 4.1. $NO_X$ concentration maps and micro–scale stagnation effects

The maps of daily average $NO_X$ concentration (i.e. the average of the 24 hourly runs of the MSS simulation) in the first atmospheric layer, obtained from the simulation of the emissions of all three future plant sources, for the two test days, are shown in Figure 3.

***Table 1.*** *Exhaust gas temperature and velocity (average daily values) at the exit of the three device stacks on January 14th and February 6th 2010. The tri–generator operates at steady–state conditions throughout the day*

| Device | Exhaust Gas Conditions–Jan 14th | | Exhaust Gas Conditions–Feb 6th | |
|---|---|---|---|---|
| | Temperature (°C) | Velocity (m/s) | Temperature (°C) | Velocity (m/s) |
| Boiler | 93 | 2.3 | 76 | 1.3 |
| Steam Generator | 195 | 2.5 | 190 | 2.3 |
| Tri–Generator | 125 | 16.1 | 125 | 16.1 |

Because of low wind conditions occurring on January 14th, the plumes are mainly driven by dispersion and spread at ground with no preferential direction. On the contrary, on February 6th, the prevailing wind direction is clearly visible, since moderate wind conditions occur. It would be expected the pollutant accumulation to be higher in the 14th January scenario, when in fact the maximum hourly simulated $NO_X$ concentration value (80.5 μg/m$^3$) results and is reached at 23:00. Nevertheless, the average daily concentration maximum is higher during the February case (23 μg/m$^3$) than in January 1st (9 μg/m$^3$). Pollutant stagnation phenomena clearly occur on February 6th due to the building shielding effect and to the building location with respect to the wind direction, and the $NO_X$ exhibits a local increase of concentration. Hence, as shown in Figure 3b, ground level $NO_X$ concentration peaks among two parallel buildings forming an urban canyon very close to the emission sources (the map of the investigated area is zoomed in Figure 4a).

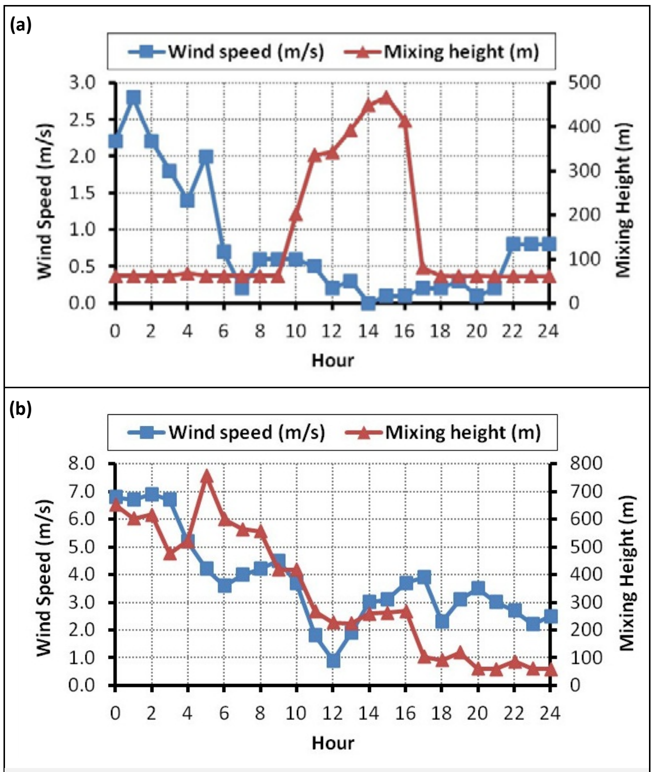


***Figure 2.*** *Meteorological dataset: hourly wind speeds and mixed layer heights for January 14th* ***(a)*** *and February 6th 2010* ***(b)****.*

Oke (1987) and Vardoulakis et al. (2003) classified different air–flow conditions within urban canyons by introducing the building aspect ratio H/W, where H is the canyon height and W the street width; in this case H=8 m and W=7 m, so that H/W~1. According to this classification, in which also wind direction respect to the canyon axis is taken into account, this is a condition of skimming flow canyon where the formation of a single eddy occurs and, consequently, turbulent recirculation prevents pollutants removal. The pattern of daily average $NO_X$ concentrations within the urban canyon was estimated by interpolation of the simulation outputs at 19 points along a longitudinal cross–section of the canyon (Figure 4a); the concentration gradient between the cavity and the open field is quite evident (Figure 4b).

Simulations performed separately for the emission sources, auxiliary devices and tri–generator unit (Ghermandi et al., 2013), show that the concentration increase in the canyon is caused mainly by the auxiliary device, since the vertical dispersion is prevented by the wind forcing; the tri–generator emissions appear almost unaffected by building because of their plume rise due to the higher tri–generator stack height and the gas exit conditions (Ghermandi et al., 2014).

Notwithstanding the plant now is not yet operational, the impact of its stack emissions to near–ground atmosphere may be preliminarily assessed by the comparison between the $NO_X$ simulated concentration and the regulatory limits for air quality. Given that regulatory limits for air quality are set by the European Directive 2008/50/EC (EU, 2008) for $NO_2$ (maximum hourly concentration 200 μg/m$^3$) instead of $NO_X$, due to the higher toxicity of the former, and that the simulated emissions are $NO_X$ (as $NO_2$), this comparison leads to a precautionary approach, since $NO_X$ includes both $NO_2$ and NO. Furthermore, the previously mentioned maximum value of hourly simulated concentration of 80.5 μg/m$^3$ is much lower than the regulatory limits.

### 4.2. Comparison with $NO_X$ measured atmospheric concentrations

The MSS performances in simulating pollutant dispersion patterns may be investigated from the comparison between the simulation outputs and the $NO_X$ atmospheric concentration measurements provided by the local Environmental Agency (ARPA) with fixed–site monitoring stations in Modena. Given that the MSS outputs represent the expected contribution to air quality only of the new power plant emissions, and no other $NO_X$ emitting source is included in the simulation, this comparison has the aim to evaluate the model reliability in simulating the effect of daily evolution of mixing height and atmospheric dynamics on the ambient $NO_X$ concentration field. Therefore, as shown later (see Figure 5), the simulated concentrations represent only a small fraction of the measured atmospheric $NO_X$, which instead results from the contribution of several urban sources, as vehicular traffic and domestic heating.

The $NO_X$ concentration measurements have been compared with the MSS maximum hourly concentrations, i.e. the spatial maximum value from every average hourly concentration map**.** In this comparison the spatial maximum instead of the spatial average of simulated concentrations was preferred, because the latter is affected by the large number of cells having very low or zero concentration over the whole simulation period (Figure 3a), leading to an impairment of the temporal comparability between the time series of spatial averages and the time series of measurements at the monitoring stations.

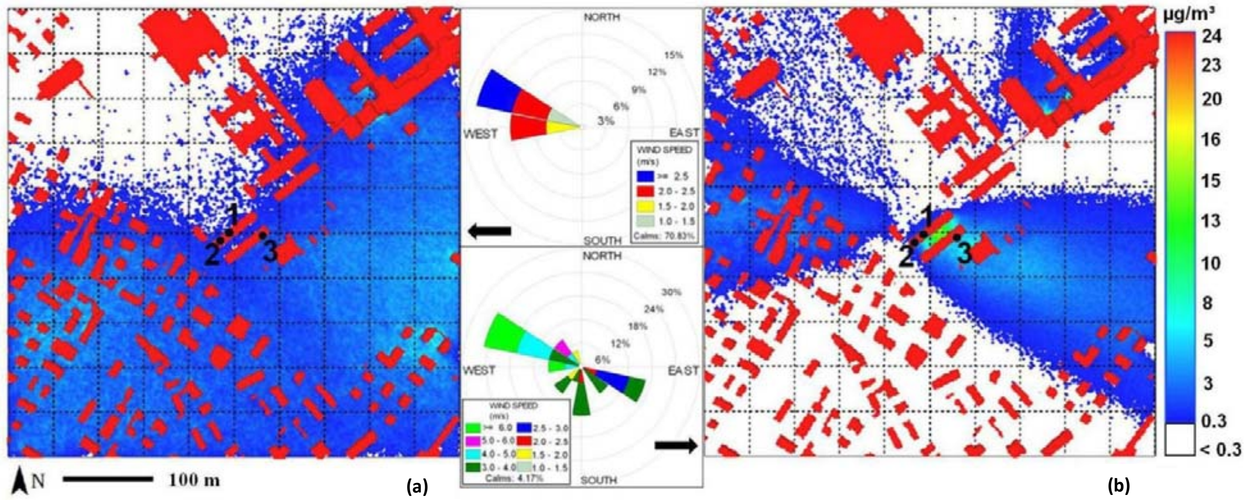


***Figure 3.*** *$NO_X$ daily average concentration maps: concentration values (µg/m$^3$) were computed on January 14th* ***(a)*** *and February 6th* ***(b)*** *2010 in the first atmospheric layer (2 m from the ground level), from all plant sources. The wind roses for the two days are also reported.*

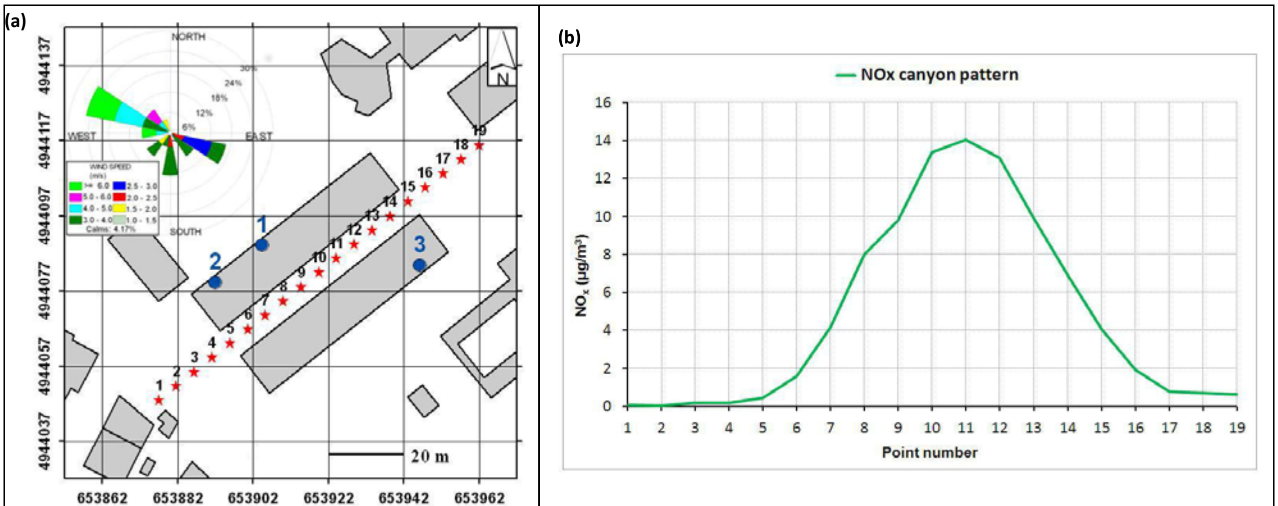


***Figure 4.*** *Focus on urban canyon: position of interpolation points on the map with wind rose* ***(a)*** *and $NO_X$ daily average concentration pattern (µg/m$^3$) on February 6th 2010 within the urban canyon* ***(b)****. The canyon effect is enhanced since wind direction is near perpendicular to the canyon axis.*

The comparison was carried out only for January 14th, 2010, when low wind conditions occurred. The atmospheric $NO_X$ concentrations used in the comparison were measured by local ARPA at a hourly time resolution, at three different fixed–site monitoring stations (Figure 5a): two of them (1 and 2) are representative for urban traffic conditions while the third (3) is an urban background site located in the largest city park. These $NO_X$ concentration measurements were compared with the MSS maximum hourly concentrations in the lowest atmospheric layer. Maximum hourly patterns from MSS simulation have been outlined for the overall contribution of the plant and separately for each source, i.e. for the auxiliary devices (boiler and steam generator) and for the tri–generation unit.

Figures 5b and 5c show the hourly patterns of measured and maximum simulated $NO_X$ concentrations on January 14th. The measured concentration peak during the hours of heavy traffic is quite evident for sites 1 and 2.

The comparison was quantitatively evaluated by the Pearson's linear correlation coefficient *r*, between hourly measured data at each site and hourly maximum concentrations for each source contribution. The correlation has been studied over two time slots: from 01:00 to 00:00 and from 01:00 to 18:00. The results are shown in Table 2.

The two data sets exhibit a good and significant ($p$–value <0.05) (Montgomery and Runger, 2007) correlation between 01:00 and 18:00, while the correlation decreases for the time slot from 01:00 to 00:00. This is due to the high value of simulated concentrations in late afternoon and evening for cells adjacent to the buildings (Figure 5c), where the local atmospheric stability reduces air mixing, leading to pollutant accumulation; moreover the ARPA stations for air quality monitoring, as required by the European Directive on ambient air quality (EU, 2008), are not placed very close to buildings. Consequently, the measured data show a maximum during traffic rush hours (from 06:00 to 09:00, Figure 5b) and an almost steady trend for the rest of the day.

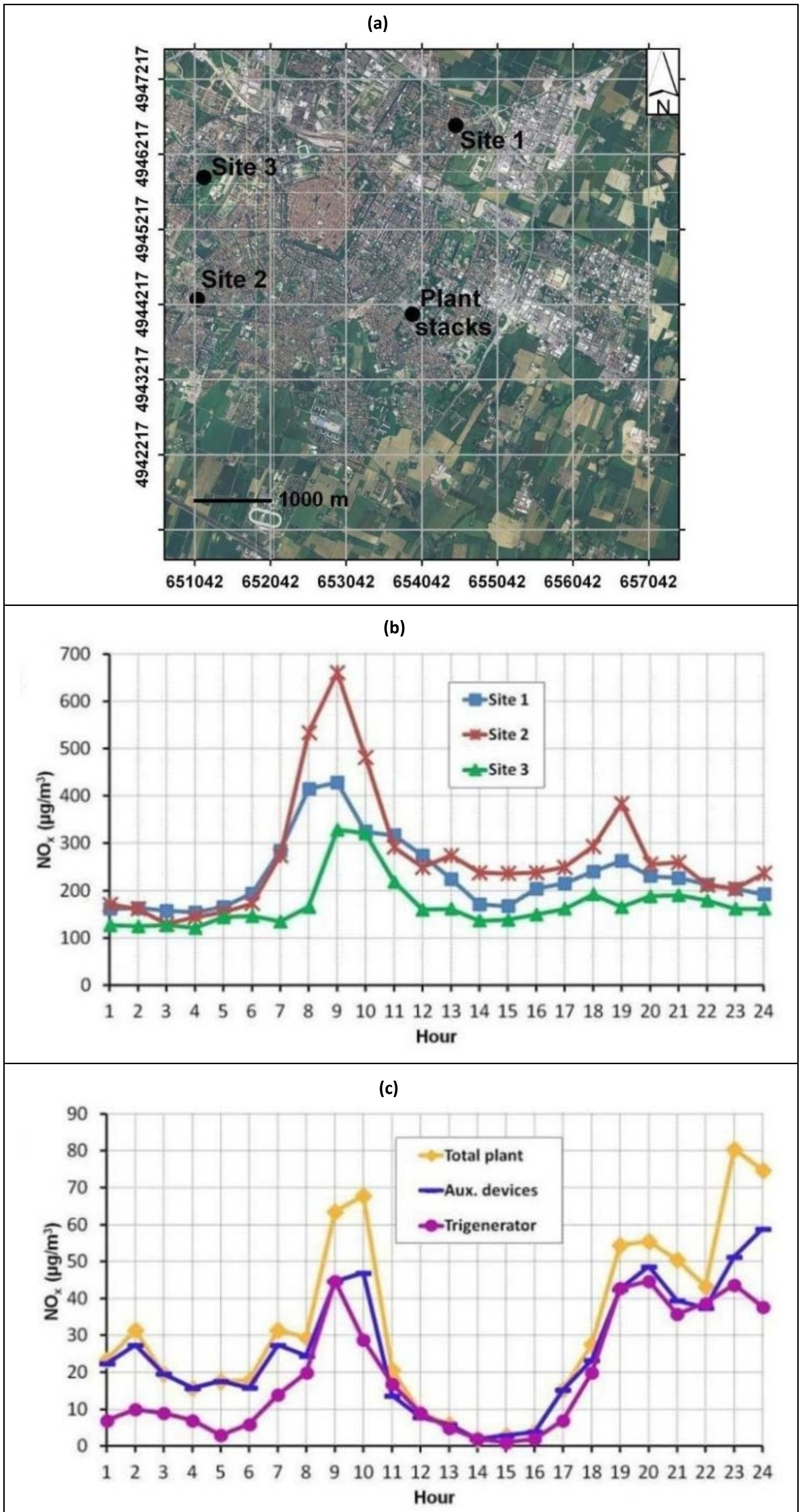


***Figure 5.*** *Comparison of measured and simulated data: geographical map with power-plant stack and fixed-site monitoring station position **(a)**, $NO_X$ hourly concentration patterns on January 14$^{th}$ 2010 outlined from the three measuring sites **(b)**, and from the simulated data **(c)**.*

***Table 2.*** *Pearson's correlation coefficient between measured data and hourly maximum concentration peaks (for total plant and auxiliary devices and tri–generator unit separately) over two time slots: from 01:00 to 00:00 and from 01:00 to 18:00. Boldfaced values indicate statistically significant correlation (p–value<0.05) (Montgomery and Runger, 2007)*

| Emitting Source | 01:00–00:00 | | | 01:00–18:00 | | |
|---|---|---|---|---|---|---|
| | Site 1 | Site 2 | Site 3 | Site 1 | Site 2 | Site 3 |
| All plant sources | 0.33 | 0.38 | **0.53** | **0.63** | **0.69** | **0.80** |
| Auxiliary devices | 0.27 | 0.32 | **0.45** | **0.55** | **0.60** | **0.69** |
| Tri–generator unit | **0.42** | 0.45 | **0.54** | **0.83** | **0.86** | **0.87** |

Best correlations are obtained for site 3, since it is less influenced by traffic emissions and is representative of urban background conditions, i.e. also for residential urban areas, as it is the case of the simulation domain. Concerning the contribution of the different sources, the maximum correlation occurs for the tri–generation unit, which operates at constant loading rate through-out the day: given the steady emission rate from this unit stack, the strength of its impact on air quality will be mainly driven by meteorological conditions. On the contrary, the auxiliary devices operate at variable loading rate during the day, with highs in the early morning, and their impact will be also significantly affected by their emission rate trend.

The correlation shown in Table 2 further improves and maintains its significance if only the time slot from 08:00 to 16:00 is considered (*r* always larger than 0.85 and *p*–value<0.05) although in this case the number of data used is limited: in this time slot the auxiliary devices operate at less variable loading rate and atmospheric conditions are more favorable to dispersion. These outcomes confirm the reliability of MSS to simulate the daily evolution of atmospheric dispersion pattern (Tinarelli et al., 2012).

## 5. Conclusions

This study deals with a micro–scale simulation of atmospheric dispersion for $NO_X$ emissions from a power plant, designed to supply the energy demand of Modena General Hospital (Central Po Valley, Italy), that will be activated in the future. Emission data were deduced from the yearly plan of operation according to expected daily fuel consumption assumed for plant design. Simulations span over two daily periods (24 hours) which were chosen by analyzing the winter 2010 meteorological dataset. The goal was to identify the different role of urban obstacles in affecting dispersion patterns under different meteorological scenarios, depending on whether low or moderate wind conditions occur. Simulations were performed via the software package Micro–Swift–Spray provided by Arianet s.r.l for micro–scale applications.

When atmospheric conditions are unfavorable for dispersion (January 14$^{th}$), pollutant plumes tend to stagnate and merge in the surroundings of the sources. Under the February 6$^{th}$ meteoro-logical scenario, when windy conditions occur, plumes appear more stretched along wind prevailing direction and building influence on air flow becomes significant. A skimming flow canyon phenomenon causes a local increase of $NO_X$ concentration. Such results show that, at micro–scale, the combined effect of urban obstacles with stacks emissions may cause pollutant stagnation in urban canyons, especially in windy conditions when, on the contrary, more favorable conditions for pollutant dispersion should be expected.

Atmospheric levels of $NO_X$ due to plant emissions and simulated by MSS are much lower than regulatory limits and also than $NO_X$ observations in Modena, where near–ground air quality is strongly affected by traffic emissions.

The qualitative comparison carried out on January 14$^{th}$ between hourly patterns of maximum concentration peaks and measured data in urban environment show a good correlation, especially during daylight hours, indicating the MSS reliability in simulating both the atmospheric mixing conditions and the dispersion patterns within an urban environment.

## References


Anfossi, D., Ferrero, E., Brusasca, G., Marzorati, A., Tinarelli, G., 1993. A simple way of computing buoyant plume rise in Lagrangian stochastic dispersion models. *Atmospheric Environment Part A–General Topics* 27, 1443–1451.

Arianet, 2010. SPRAY5 – General Description and User's Guide, 143 pages.

Aria Technologies, 2010. SWIFT Wind Field Model, General Design Manual, 89 pages.

Bigi, A., Ghermandi, G., Harrison, R.M., 2012. Analysis of the air pollution climate at a background site in the Po Valley. *Journal of Environmental Monitoring* 14, 552–563.

Chandrasekar, A., Philbrick, C.R., Clark, R., Doddridge, B., Georgopoulos, P., 2003. Evaluating the performance of a computationally efficient MM5/CALMET system for developing wind field inputs to air quality models. *Atmospheric Environment* 37, 3267–3276.

Deserti, M., Cacciamani, C., Golinelli, M., Kerschbaumer, A., Leoncini, G., Savoia, E., Selvini, A., Paccagnella, T., Tibaldi, S., 2001. Operational meteorological pre–processing at Emilia–Romagna ARPA Meteorological Service as a part of a decision support system for air quality management. *International Journal of Environment and Pollution* 16, 571–582.

E.R. (Emilia Romagna), 2011. Topographic Database 2011, Emilia Romagna Region, Version 1.0, 295 pages.

EU (European Union), 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on Ambient Air Quality and Cleaner Air for Europe, Official Journal of the European Union, L152/1–L152/44.

EU (European Union), 2004. Directive 2004/8/EC of the European Parliament and of the council of 11 February 2004 on the Promotion of Cogeneration Based on a Useful Heat Demand in the Internal Energy Market and Amending Directive 92/42/EEC. Official Journal of the European Union, L52/50–L52/60.

Ferrero, L., Riccio, A., Perrone, M.G., Sangiorgi, G., Ferrini, B.S., Bolzacchini, E., 2011. Mixing height determination by tethered balloon–based particle soundings and modeling simulations. *Atmospheric Research* 102, 145–156.

Ghermandi, G., Teggi, S., Fabbi, S., Bigi, A., Zaccanti, M.M., 2014. Tri–generation power plant and conventional boilers: Pollutant flow rate and atmospheric impact of stack emissions in *International Journal of Environmental Science and Technology*, Springer Berlin Heidelberg, pp. 1–12.

Ghermandi, G., Teggi, S., Fabbi, S., Bigi, A., Zaccanti, M. M., 2013. From local–scale to micro–scale assessment of the atmospheric impact of the pollutant plume emitted from a power–plant stack. *Proceedings of 15$^{th}$ International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, May 6–9, 2013, Madrid, Spain, pp. 579–583.

Hanna, S., White, J., Trolier, J., Vernot, R., Brown, M., Gowardhan, A., Kaplan, H., Alexander, Y., Moussafir, J., Wang, Y.S., Williamson, C., Hannan, J., Hendrick, E., 2011. Comparisons of JU2003 observations with four diagnostic urban wind flow and Lagrangian particle dispersion models. *Atmospheric Environment* 45, 4073–4081.

Montgomery, D.C., Runger, G.C., 2007. *Applied Statistics and Probability for Engineers*, John Wiley & Sons Inc., USA, pp. 768.

Moussafir, J., Oldrini, O., Tinarelli, G., Sontowski, J., Dougherty, C., 2004. A new operational approach to deal with dispersion around obstacles: the MSS (Micro–Swift–Spray) software suite. *Proceedings of 9th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, June 1–4, 2004, Garmisch, Germany.

Oke, T.R., 1987. *Boundary Layer Climates*, Routledge, Cambrigde, UK, pp. 435.

Thomson, D.J., 1987. Criteria for the selection of stochastic–models of particle trajectories in turbulent flows. *Journal of Fluid Mechanics* 180, 529–556.

Tinarelli, G., Mortarini, L., Trini Castelli, S., Carlino, G., Moussafir, J., Olry, C., Armand, P., Anfossi, D., 2012. Review and validation of microspray, a Lagrangian particle model of turbulent dispersion, in *Lagrangian Modeling of the Atmosphere*, Geophysical Monograph Series, 200, edited by American Geophysical Union (AGU), Grindelwald, Switzerland, pp. 311–327.

Tinarelli, G., Anfossi, D., Trini Castelli, S., Albergel A., Ganci F., Belfiore, G., Moussafir, J., 2008. Development of a Lagrangian particle model for dense gas dispersion in urban environment. *Proceedings of the 29th NATO/CCMS International Technical Meeting on Air Pollution Modelling and Its Applications*, September 24–27, 2007, Aveiro, Portugal, pp. 28–36.

Tinarelli, G., Brusasca, G., Oldrini, O., Anfossi, D., Trini Castelli, S., Moussafir, J., 2007. Micro–Swift–Spray (MSS) a new modelling system for the simulation of dispersion at microscale, general description and validation. *Proceedings of the 27th NATO/CCMS International Technical Meeting* on Air Pollution Modeling and I*ts Applications*, October 24–29, 2004, Banff, Canada, pp. 449–558.

Vardoulakis, S., Fisher, B.E.A., Pericleous, K., Gonzalez–Flesca, N., 2003. Modelling air quality in street canyons: A review. *Atmospheric Environment* 37, 155–182.